Recent developments in the Photosynthesis scheme of ORCHIDEE

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Motivations

① To implement an analytical solution solving jointly the assimilation, the stomatal conductance and the intercellular CO2 concentration

② To update the parameterisation and the formalism used, in better agreement with recent experiment-based studies

③ To better document the overall associated module

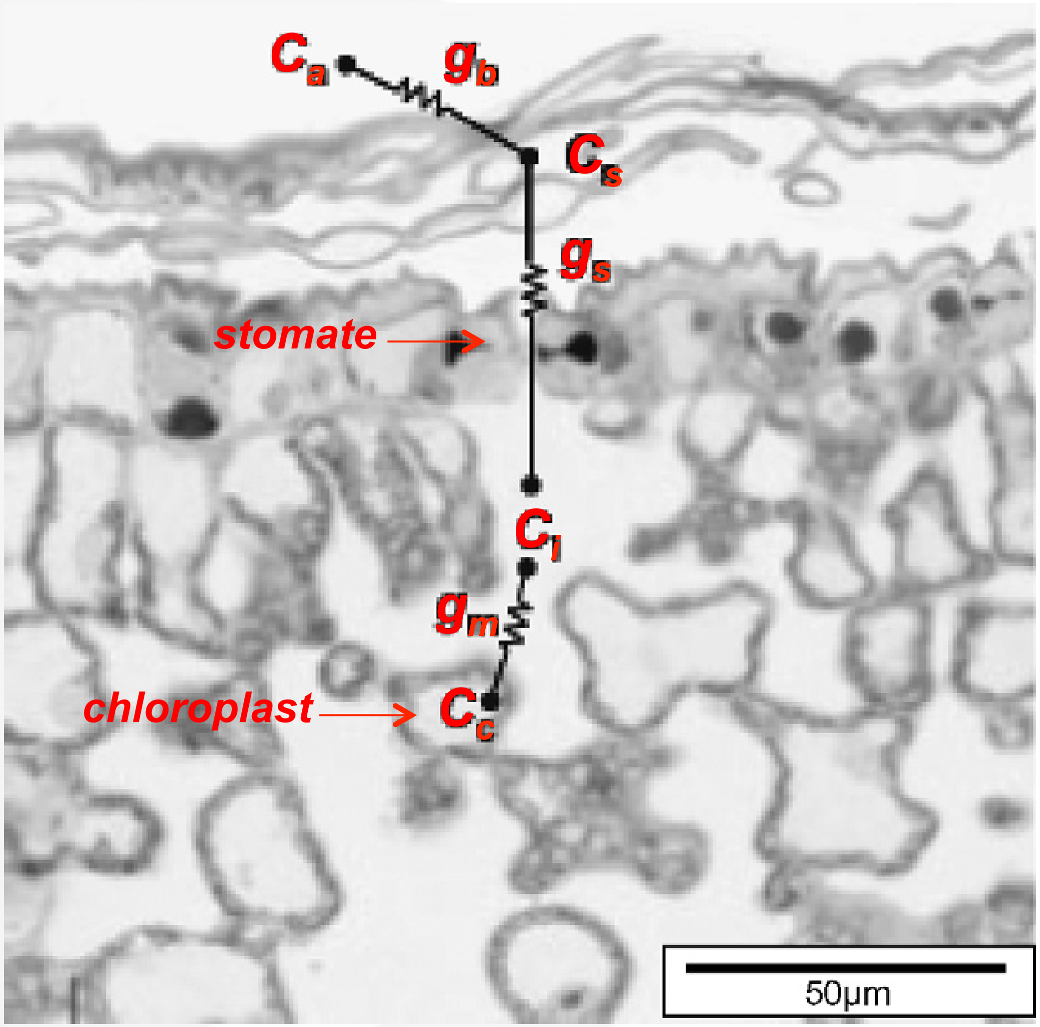
Three unknowns, three equations

- The rate of $[CO_2]$ assimilation, A
  - $A = \min(A_c, A_j)$ *where A_C is the Rubisco-limited rate of CO_2 assimilation and A_j is the e- transport-limited rate of CO_2 assimilation*
    - *Both A_c and A_j are function of C_i*

- The intercellular CO_2 partial pressure, C_i
  - $C_i = C_a - A\ (1/g_b + 1/g_s)$ where C_s is the leaf-surface CO_2 partial pressure, g_b the boundary-layer conductance

- The stomatal conductance, g_s
  - $g_s = g_0 + (A + R_d) / (C_i - C^*_i)\ f_{VPD}$ where g_0 is the stomatal conductance when irradiance is 0 and R_d the dark respiration

Conductances and $[CO_2]$ within the leaf



- C_a : Ambient air CO_2 partial pressure
- C_s : Leaf surface CO_2 partial pressure
- C_i : Intercellular CO_2 partial pressure
- C_c : Chloroplast CO_2 partial pressure
- g_b : Boundary-layer conductance
- g_s : Stomatal conductance
- g_m : Mesophyll diffusion conductance

Solving A, g_s and C_i

- Often done by numerical iteration approach
- In ORCHIDEE, an approximate solution was calculated, using the C_i value of the former time step with a “relaxation” term
- Combining the 3 equations leads to a standard cubic equation for A : $A^3 + pA^2 + qA + r = 0$ (more details in Baldocchi (1994))
- Yin et al. (2009) propose an analytical solution for C_3 and C_4 plants (All the details in the Appendix of Yin et al.)
  - Three roots, one being most suitable for solving both A_c or A_j under any combination of C_i, radiation, temperature and VPD.

Temperature response of photosynthesis parameters

- Two types of equations are commonly used

Arrhenius function

$$f(T_k) = k_{25} \exp\left(\frac{E_a (T_k - 298)}{298 R T_k}\right)$$

Function used for the all temperature-dependant parameters except Vc_{max} and J_{max}

Peak function

$$f(T_k) = k_{25} \exp\left(\frac{E_a (T_k - 298)}{298 R T_k}\right) \frac{1 + \exp\left(\frac{298 \Delta S - E_d}{298 R}\right)}{1 + \exp\left(\frac{T_k \Delta S - E_d}{T_k R}\right)}$$

Function used for Vc_{max} and J_{max}

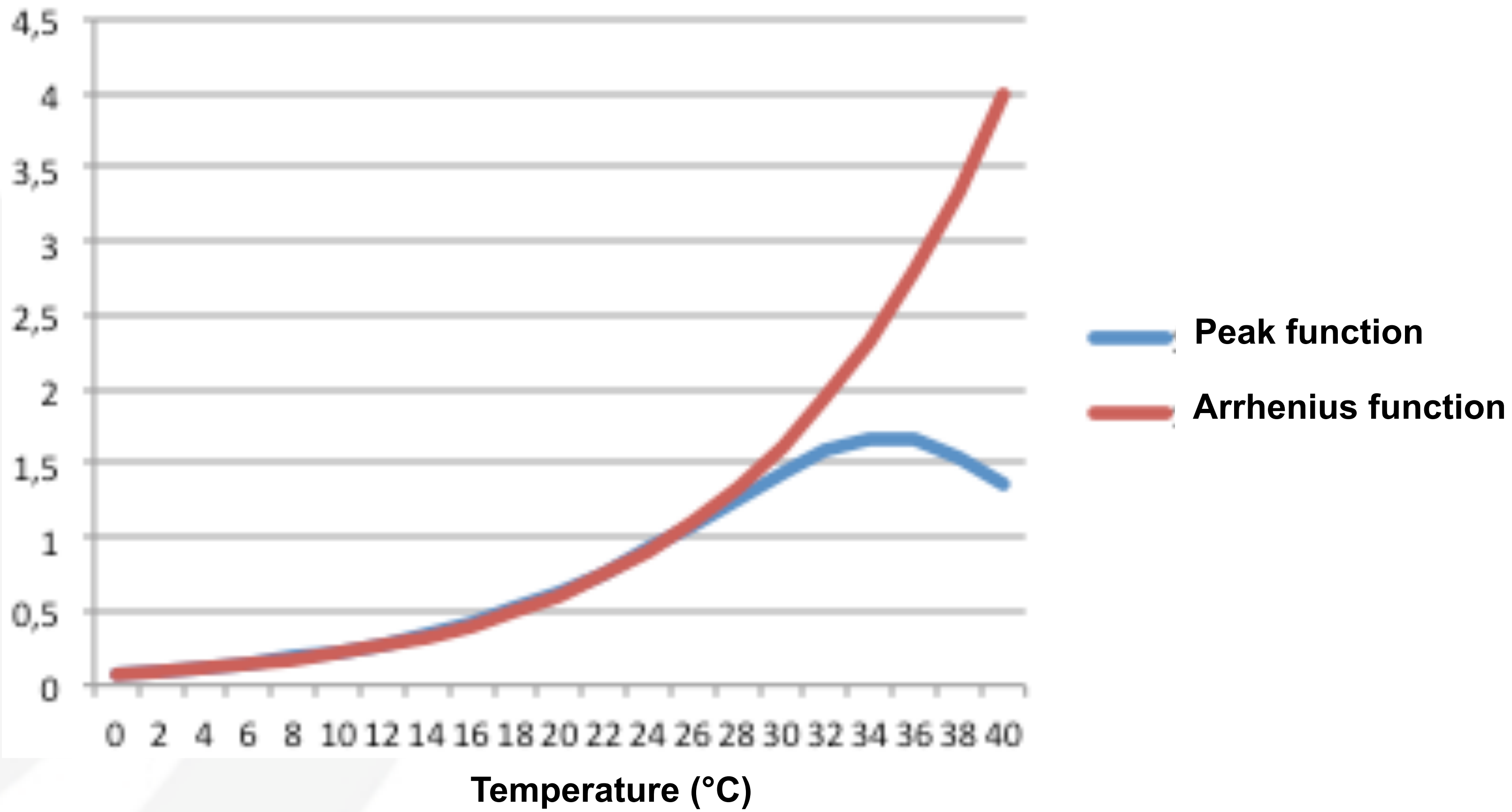
E_a : Activation energy

E_d : Deactivation energy

ΔS : entropy factor

Temperature response of photosynthesis parameters

- **Arrhenius vs. Peak functions**



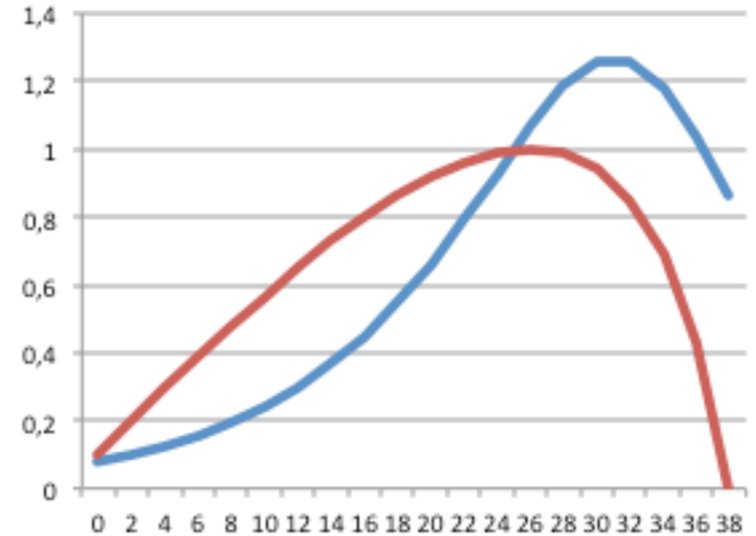
Temperature response of photosynthesis parameters

- Formerly, in ORCHIDEE, temperature response for Vc_{max} and J_{max} (for C3 species) is defined using T_{min}, T_{max} and T_{opt} with the following equation

$$f(T) = k_{opt} \frac{(T - T_{\min})(T - T_{\max})}{(T - T_{\min})(T - T_{\max}) - (T - T_{opt})^2}$$

Peak function with E_a = 71500 J mol^{-1}
ΔS = 653 J mol^{-1} K^{-1}
E_d = 200000 J mol^{-1}

“Old” function with T_{min}=-2°C
T_{max}=38°C
T_{opt}=25°C



- For C4 species, the former temperature response is a peak function => no change

Temperature response of photosynthesis parameters

- From reference value at 25°C to reference value at T_{opt} (see Medlyn et al., 2002)

$$f(T_k) = k_{25} \exp\left(\frac{E_a (T_k - 298)}{298 R T_k}\right) \frac{1 + \exp\left(\frac{298 \Delta S - E_d}{298 R}\right)}{1 + \exp\left(\frac{T_k \Delta S - E_d}{T_k R}\right)}$$

$$f(T_k) = k_{opt} \frac{E_d \exp\left(\frac{E_a (T_k - T_{opt})}{T_k R T_{opt}}\right)}{E_d - E_a \left(1 - \exp\left(\frac{E_d (T_k - T_{opt})}{T_k R T_{opt}}\right)\right)}$$

with $T_{opt} = \dfrac{E_d}{\Delta S - R \ln\left(\dfrac{E_d}{(E_d - E_a)}\right)}$ in Kelvin

Temperature acclimation

- Response to long-term temperature
- Formerly in ORCHIDEE, only for C3 grass : T_{min}, T_{max} and T_{opt} are function of the long-term temperature
- Kattge & Knorr (2007) analysed data, searching for temperature acclimation of Vc_{max} and J_{max} related parameters
  - $Vc_{max,25}$
  - $J_{max,25}$
  - T_{opt}
  - ΔS_{Jmax} and ΔS_{Vcmax}
  - $J_{max,25} / Vc_{max,25}$

$$p = a + b \times t_{growth}$$

with t_{growth} the monthly temperature (°C)

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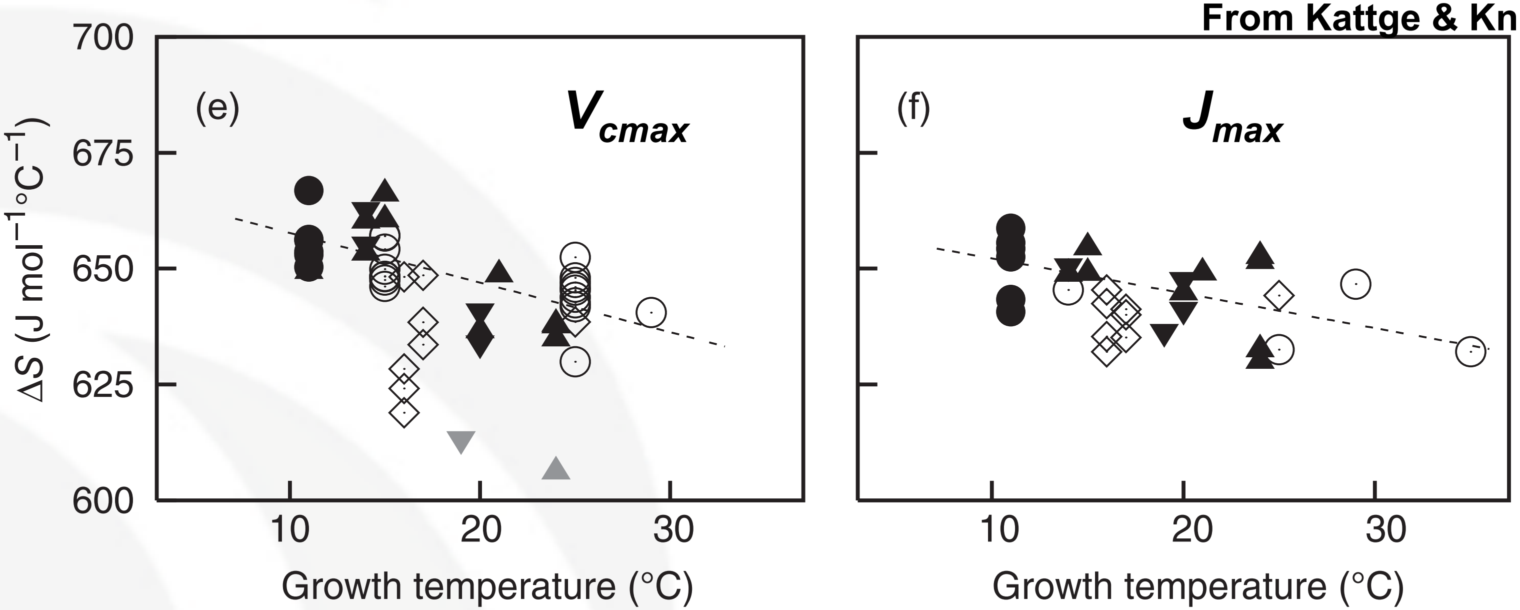
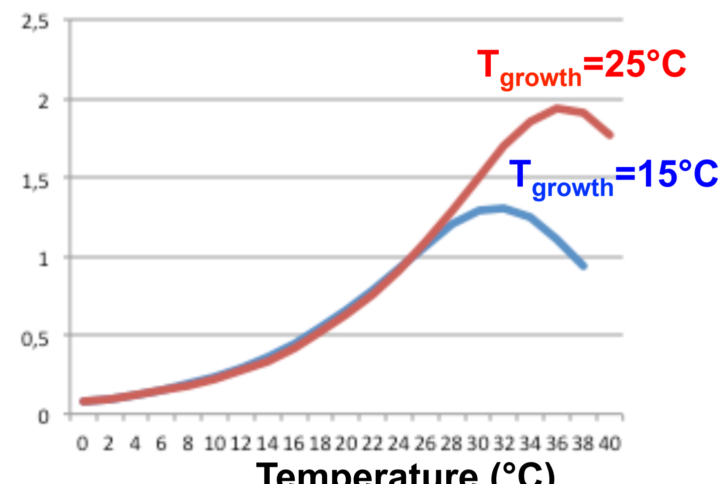
Temperature acclimation: *ΔS parameter*

From Kattge & Knorr (2007)



$$\Delta S_{Vcmax} = 668 - 1.07\ t_{growth}$$

$$\Delta S_{Jmax} = 660 - 0.75\ t_{growth}$$

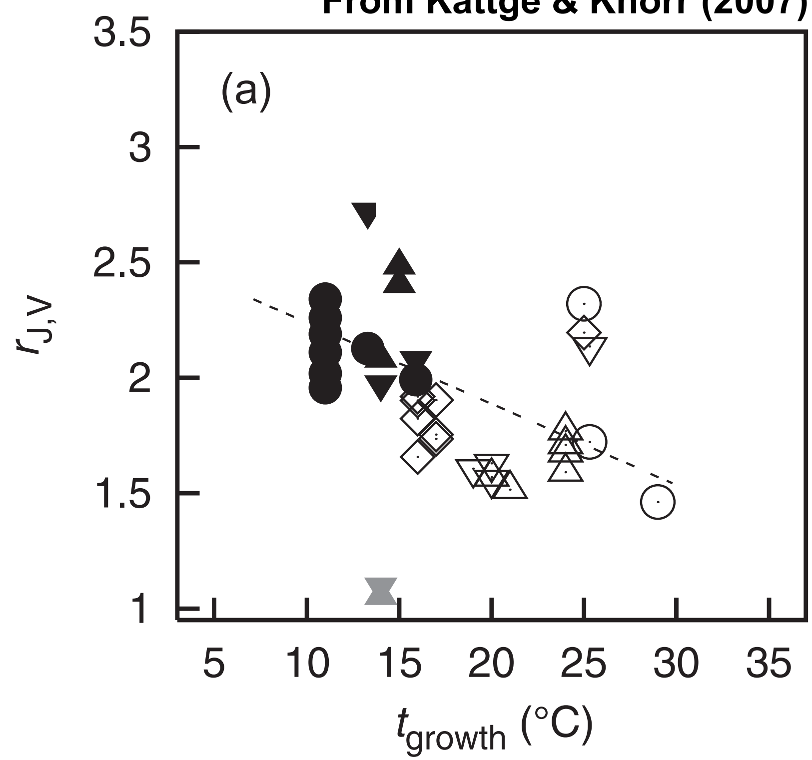


Temperature acclimation: $r_{j,v}$ *parameter*

$$r_{j,v} = 2.59 - 0.035\ t_{growth}$$

$$r_{j,v} = 1.7 \text{ for } t_{growth} = 25°C$$
$$r_{j,v} = 2.0 \text{ for } t_{growth} = 15°C$$

From Kattge & Knorr (2007)



Parameterization used

- Most parameter values used are those from Yin et al. (2009), Bernacchi et al. (2001), Medlyn et al. (2002) and Kattge & Knorr (2007)

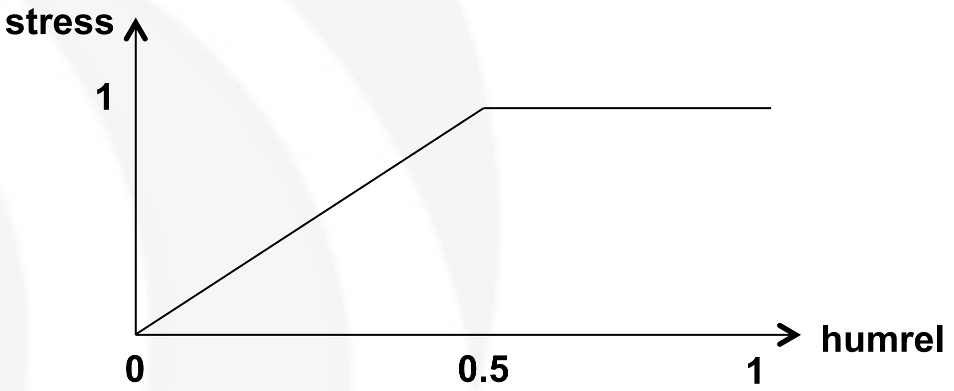
- Formalism and associated parameterization used by Medlyn et al. and Kattge & Knorr do not account for the mesophyl conductance while Yin et al. do => so far, we neglect g_m

- We use a peak function for the sensitivity to temperature for both V_{cmax} and J_{max} (Yin et al. assume an Arrhenius function for V_{cmax})

- No acclimation for C4 species

Effects of other factors

- Water stress
  - few studies: see Keenan et al., 2010
  - Impacts on Vc_{max} and J_{max} based on relative soil moisture.
  - We keep the formulation used formerly in ORCHIDEE



- Nitrogen stress
  - There is no explicit representation of nitrogen but we do account for a reduction of Vc_{max} and J_{max} within the canopy assuming that leaf N is decreasing from top to bottom canopy

From leaf to canopy

- A and g_s are calculated at each LAI level
- Beer-Lambert decrease of light in the canopy :

$$I_l = I_0 \exp(-kl)$$

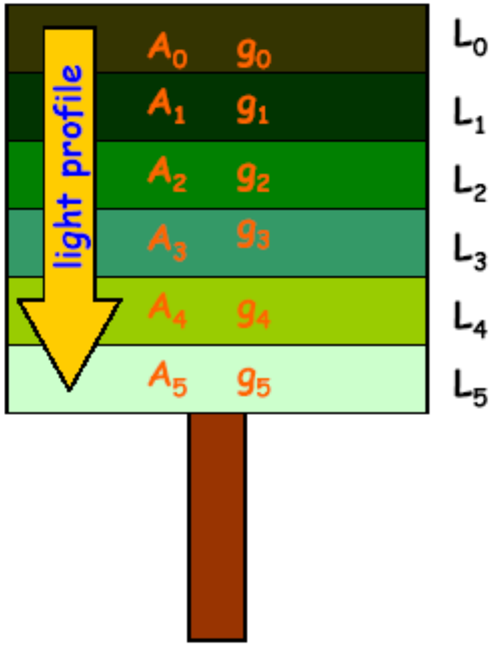
with k=0.5

=> see Spitters (1986)

- N-limitation of assimilation, f_N

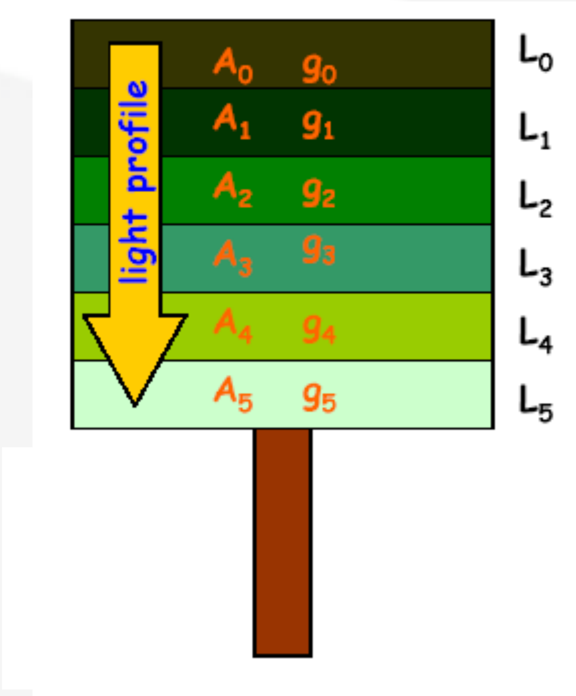
$$f_N = 1 - 0.7\left(1 - \exp(-kl)\right)$$

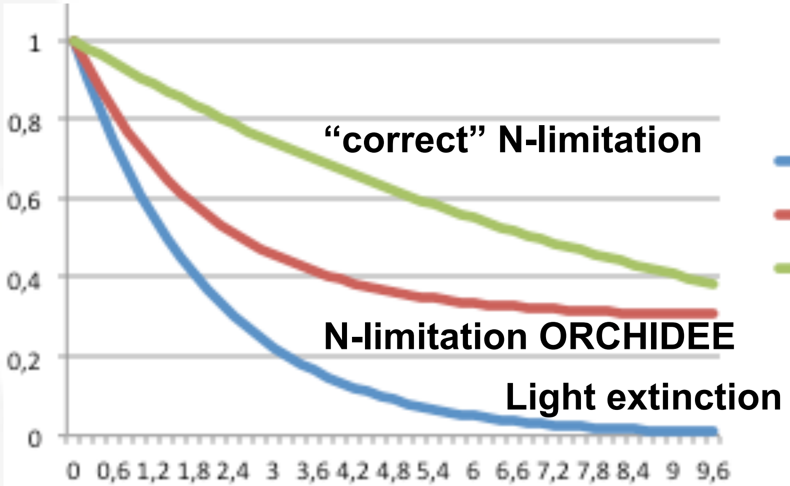
- The others parameters (e.g temperature, CO_2, VPD, ...) are held constants.



From leaf to canopy

- N-limitation of assimilation





See Dewar et al., 2002

Code management

- The new scheme has been merged in the trunk
  - Revision 2031 – April 2014
- No epxlicit documentation (yet) but the references used are cited both in the diffuco_trans_co2 routine and in the parameter module

```
REAL(r_std), PARAMETER, DIMENSION(nvmc) :: E_KmC_mtc  = &        !! Energy of activation for KmC (J mol-1)
& (/undef,  79430.,  79430.,  79430.,  79430.,  79430.,  79430.,  &   !! See Medlyn et al. (2002)
&  79430.,  79430.,  79430.,  79430.,  79430.,  79430.  /)            !! from Bernacchi al. (2001)

REAL(r_std), PARAMETER, DIMENSION(nvmc) :: E_KmO_mtc  = &        !! Energy of activation for KmO (J mol-1)
& (/undef,  36380.,  36380.,  36380.,  36380.,  36380.,  36380.,  &   !! See Medlyn et al. (2002)
&  36380.,  36380.,  36380.,  36380.,  36380.,  36380.  /)            !! from Bernacchi al. (2001)

REAL(r_std), PARAMETER, DIMENSION(nvmc) :: E_gamma_star_mtc  = &   !! Energy of activation for gamma_star (J mol-1)
& (/undef,  37830.,  37830.,  37830.,  37830.,  37830.,  37830.,  &   !! See Medlyn et al. (2002) from Bernacchi al. (2001)
&  37830.,  37830.,  37830.,  37830.,  37830.,  37830.  /)            !! for C3 plants - We use the same values for C4 plants

REAL(r_std), PARAMETER, DIMENSION(nvmc) :: E_Vcmax_mtc  = &      !! Energy of activation for Vcmax (J mol-1)
& (/undef,  71513.,  71513.,  71513.,  71513.,  71513.,  71513.,  &   !! See Table 2 of Yin et al. (2009) for C4 plants
&  71513.,  71513.,  71513.,  67300.,  71513.,  67300.  /)            !! and Kattge & Knorr (2007) for C3 plants (table 3)

REAL(r_std), PARAMETER, DIMENSION(nvmc) :: E_Jmax_mtc  = &        !! Energy of activation for Jmax (J mol-1)
& (/undef,  49884.,  49884.,  49884.,  49884.,  49884.,  49884.,  &   !! See Table 2 of Yin et al. (2009) for C4 plants
&  49884.,  49884.,  49884.,  77900.,  49884.,  77900.  /)            !! and Kattge & Knorr (2007) for C3 plants (table 3)

REAL(r_std), PARAMETER, DIMENSION(nvmc) :: aSV_mtc     = &        !! a coefficient of the linear regression (a+bT) defining the Entropy
erm for Vcmax (J K-1 mol-1)
& (/undef,  668.39,  668.39,  668.39,  668.39,  668.39,  668.39,  &   !! See Table 3 of Kattge & Knorr (2007)
&  668.39,  668.39,  668.39,  641.64,  668.39,  641.64  /)            !! For C4 plants, we assume that there is no
                                                                       !! acclimation and that at for a temperature of 25Â°C, aSV is the same
or both C4 and C3 plants (no strong jusitification - need further parametrization)
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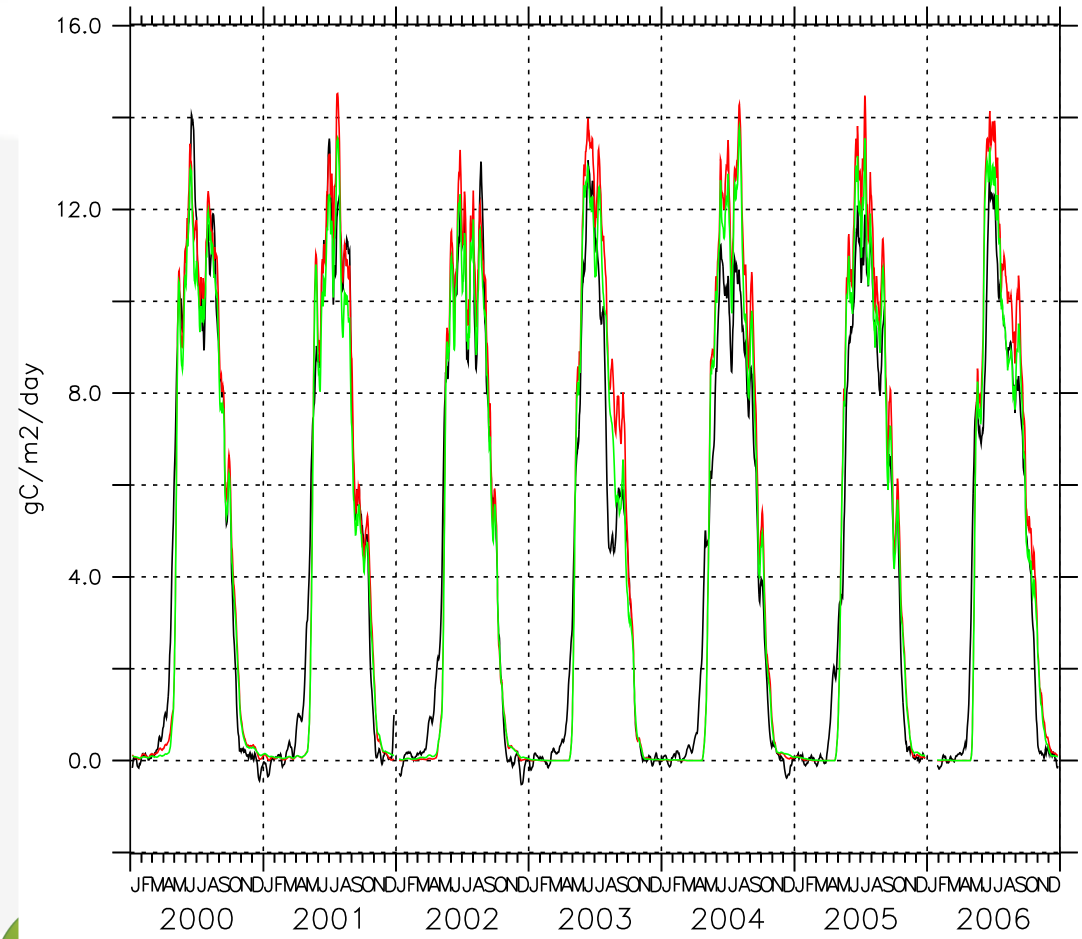
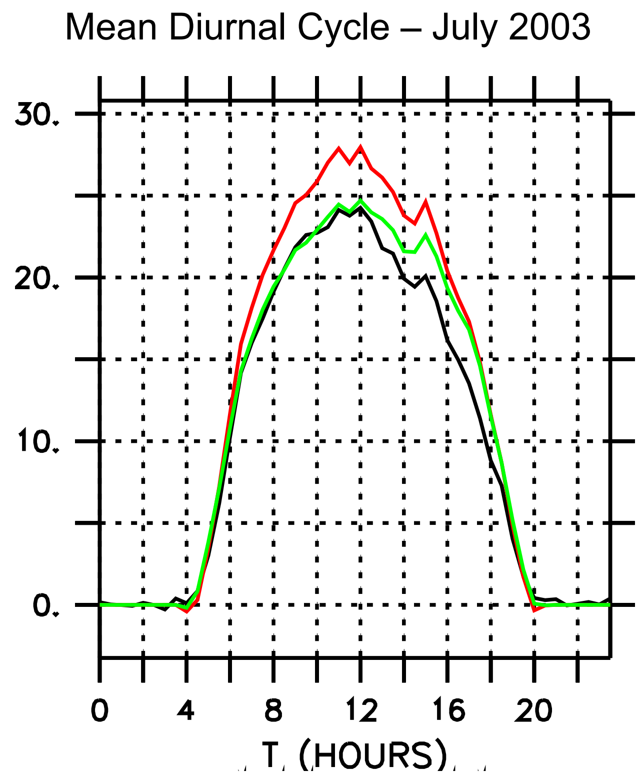
Evaluation of the modified scheme

- <u>At site level</u> GPP @ Hainich (Germany)

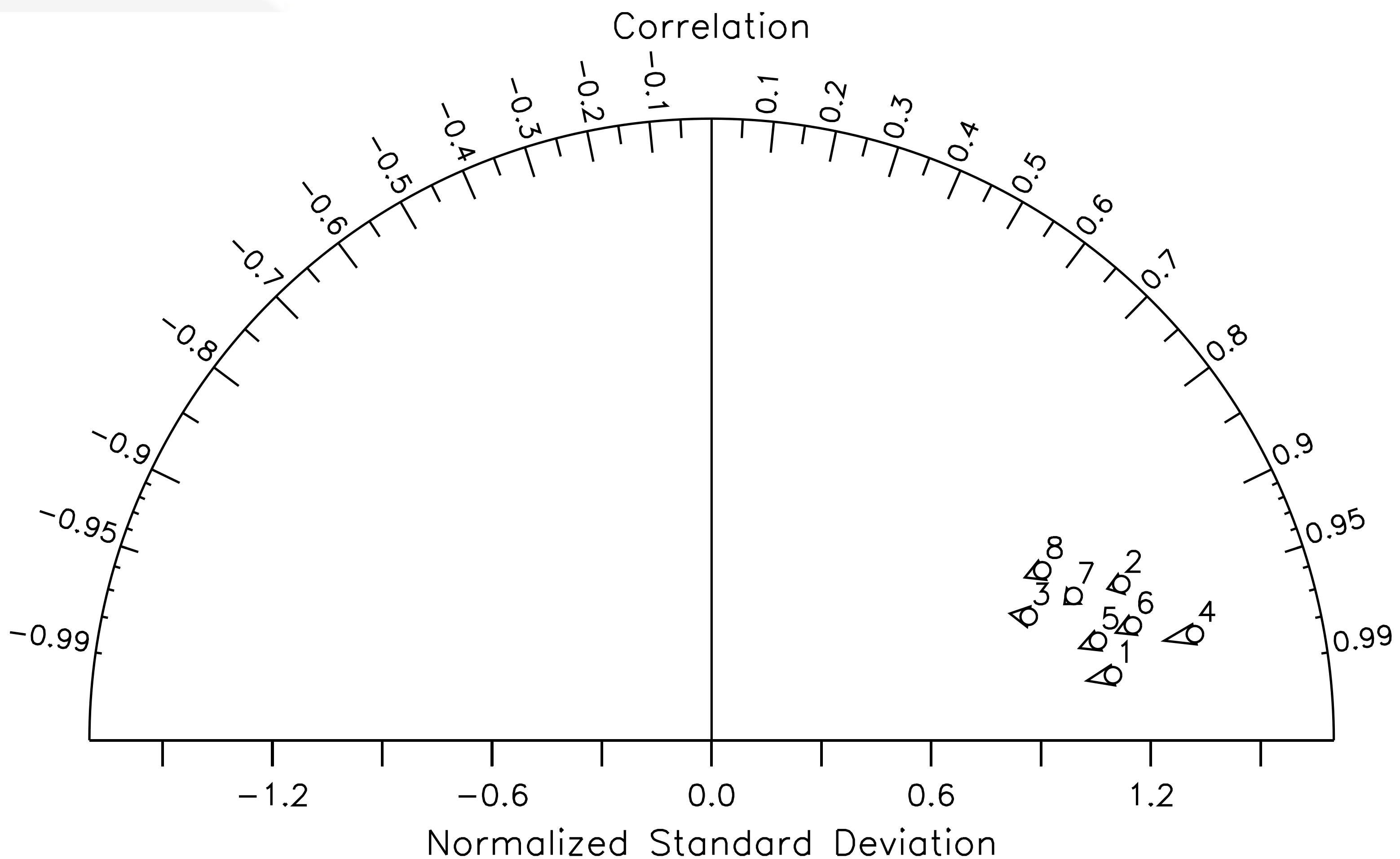




Evaluation of the modified scheme

- <u>At site level</u> DBF sites: month-to-month GPP variability

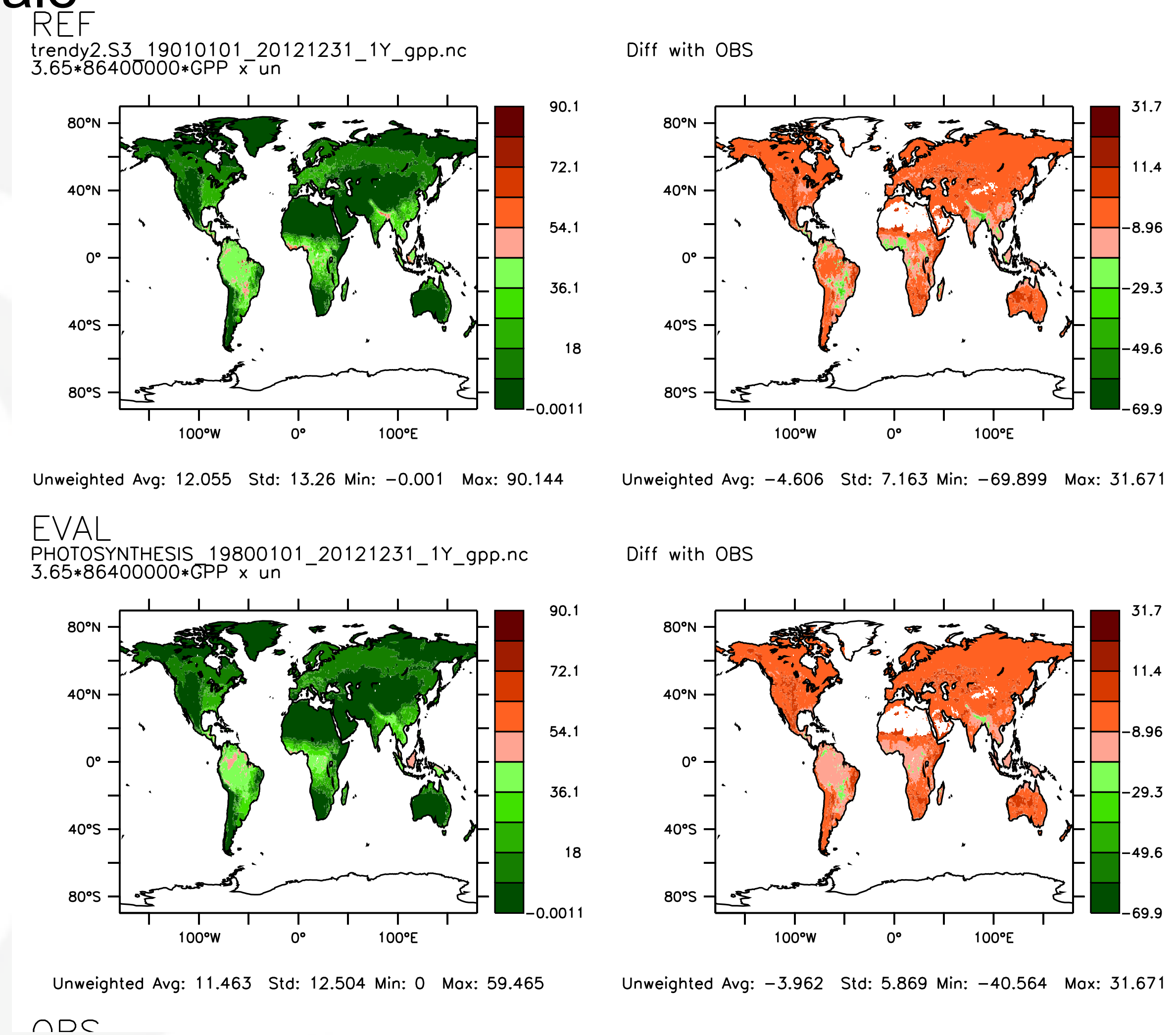
1 DE−Hai
2 IT−Ro1
3 IT−Ro2
4 US−Bar
5 US−Ha1
6 US−MMS
7 US−WBW
8 US−WCr



- At global scale

Old Scheme

New Scheme



Further improvements

- Modifying the vertical profile of the leaf Nitrogen within the canopy
- Optimization of the current scheme:
  - Vcmax,25
  - Acclimation parameters for $Vc_{max,25}/J_{max,25}$, S_{Vcmax}, S_{Jmax}
- Accounting for mesophyll conductance and its effect on assimilation
- Accounting for partitioning between diffuse and direct light within the canopy

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